FINAL TECHNICAL REPORT

FOR

OFFICE OF NAVAL RESEARCH

The Jamie Whitten National Center for Physical Acoustics

The
University of Mississippi

FINAL TECHNICAL REPORT

FOR

OFFICE OF NAVAL RESEARCH

CONTRACT N00014-93-1-0569

ENTITLED

NCPA RESEARCH, FY93

JUNE 1995

NCPA Internal Tracking Number: LC695-1

National Center for Physical Acoustics
University of Mississippi and
Mississippi Resource Development Corporation

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
20 JUNE 1995

3. REPORT TYPE AND DATES COVERED
FINAL TECHNICAL 01 MAR 93 - 28 FEB 94

4. TITLE AND SUBTITLE
FINAL TECHNICAL REPORT FOR ONR

5. FUNDING NUMBERS
PE 61153N
G N00014-93-1-0569
TA 93-124-10-20
A100124---19

6. AUTHOR(S)
H.E. BASS, A.M. KOLAINI, J.M. SABATIER, F.D. SHIELDS

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
JAMIE WHITTEN NATIONAL CENTER FOR PHYSICAL ACOUSTICS
UNIVERSITY OF MISSISSIPPI
COLISEUM DRIVE
UNIVERSITY, MS 38677

8. PERFORMING ORGANIZATION REPORT NUMBER
LC695-1

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
OFFICE OF NAVAL RESEARCH
CODE 1512B:UR
BALLSTON TOWER ONE
800 NORTH QUINCY STREET
ARLINGTON, VA 22217-5660

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
THIS DOCUMENT IS A FINAL TECHNICAL REPORT FOR THE MISSISSIPPI RESOURCE DEVELOPMENT CORPORATION FROM THE NATIONAL CENTER FOR PHYSICAL ACOUSTICS. DETAILS OF THE INDIVIDUAL PROJECTS ARE INCLUDED.

14. SUBJECT TERMS
ACOUSTIC DETERMINATION OF SEDIMENT PROPERTIES, ACOUSTICALLY ACTIVE SURFACES, GRADUATE FELLOWSHIPS, OCEAN ACOUSTICS, NONLINEAR WAVES

15. NUMBER OF PAGES
42

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	

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INTRODUCTION

The FY93 Research Program at the National Center for Physical Acoustics (NCPA) reflects the evolution of NCPA. A long term study of nonlinear properties of materials was terminated and replaced with a new research program in nonlinear dynamics. The goals of this new program are described under the section on New Initiatives in the Physics of Acoustics. In addition, an existing program at NCPA concerned with the properties of soils has been expanded to include acoustic determination of sediment properties. Specifically this effort is concerned with attenuation in fluid saturated sediments. This expansion of the NCPA research program resulted from termination of propagation studies and a reduced level of effort in Ocean Acoustics. These shifts reflect changes in personnel and the basic research nature of the organization.

It is our goal to maintain a broad basic research program in the physics of acoustics and exploit those basic research programs which promise to address specific Navy problems. An excellent example of vertical development and integration was the bubbles work of Dr. Crum which transferred to the more applied environment at the University of Washington where specific Naval problems could be addressed. The modest Navy investment in a number of high risk programs is justified by the few which lead to ideas and concepts which support the fleet.

In the future, we expect a continued evolution. As research becomes mature, it will transition to a development stage or will be terminated. The research program at NCPA will always be a work in progress. The following report describes that work as of the end FY93.

ACOUSTIC DETERMINATION OF SEDIMENT PROPERTIES

ABSTRACT

Much literature exists on measurements of attenuation in porous materials. The seemingly standard model to describe attenuation in porous materials is that of Biot. For much of the data, the model under predicts the magnitude of attenuation. A widely used practice is to allow the Biot moduli to have complex values to fit the Biot theory to measured data. In this work, alternative and more fundamental mechanisms of sediment attenuation than grain-to-grain motion and squeezed-film-fluid-motion are considered. Initially mass transfer between the water and saturated vapor for partially saturated sediments is investigated. Data exists which suggests that this phenomena could be significant.

INTRODUCTION

There are two ways of incorporating attenuation effects in acoustic models of sediments. This first is to write down the physical laws pertaining to that mechanism (i.e. heat conduction or viscosity) and then develop the wave equation. The second technique is much easier but avoids the use of physics; the wave number is made complex by allowing frame module to have complex values.

When an acoustic wave propagates in a sediment, damping results from physical mechanisms. The attenuation coefficient is generally expressed in the complex propagation constant or wave number. In the first technique, when, for example, the attenuation mechanism is viscosity, the imaginary part of the wave number contains the energy loss which results from the physics of the shear or friction force being proportional to the gradient in the velocity. Although not always so relevant to fluids with specific heats as high as water, heat conduction losses are similarly expressed because heat flow is proportional to the gradient in temperature. The complex wave number allows for a complex sound velocity, which includes both phase speed and attenuation. A common practice is to further write complex densities and moduli which implicitly contain the physics of viscous and heat conduction losses.

Often when the physics of attenuation is not understood, the second technique is employed. Stoll[1] has argued slippage at grain contacts or viscous effects due to squeezed fluid motion supports the arbitrary size of the imaginary part of the moduli. Resonant column experiments have been developed to measure sediment damping. It is the purpose of this research to offer explanations of additional attenuation mechanisms.

RESEARCH PROGRESS IN FY93

In the most general sense, the Biot[2] model describes the motion of a two phase porous material. Fluid viscosity and pore size are two basic properties of a fluid-filled porous material which account for attenuation. In gas-filled materials thermal conduction of the gas must also be considered. Thus far, attenuation measurements for a host of sediments materials are larger than predicted by the Biot model.[3] The analysis trend is to either assume sediment attenuation varies as the first power of frequency[4] or to allow the Biot moduli to have small complex values.[1]

Omitting such phenomena as grain-to-grain slippage and squeeze fluid motion, we believe there are additional mechanisms which can account for the underprediction of sediment attenuation in the Biot model, both of which may be supported by existing experimental data within the sediment/geophysics community.

Partially water-saturated porous materials will experience a phase transition between the liquid/vapor due to the adiabatic compression of gaseous vapor in the material at the passage of an acoustic wave. The latter affect, termed mass transfer, may be the most significant in realistic sediments, all of which contain gas producing, living and decaying, organisms.

Even in a laboratory sediment, the difficulty of removing small amounts of gas is well known.[5] Within the literature, a few examples of mass transfer have been observed. First, Mehl & Moldover[6] observed mass transfer on the walls of an impedance tube. Spencer[7] may have observed mass transfer in his attenuation measurement on sandstone where an order of magnitude reduction in attenuation was observed as very small amounts of water were evacuated and the subsequent order of magnitude increase when less than 1% water by weight was allowed to be reabsorbed by the dry sample. O'Hara[8] confirmed measurements similar to those of Spencer. Pandit and King[9] report that the absorption in room dry rocks decreased by a factor of fifty when placed under a vacuum to remove very small amounts of water. Elastic wave velocity remains almost unchanged. Stoll[1] makes similar attenuation measurements on air-dry soils and the magnitudes are similar to those of the previous researchers. Stoll attributes the attenuation he measures to grain slippage. However, it is likely that his samples contain significant amounts of water since they were not vacuum dried.

The phenomenon of sound absorption due to mass transfer is well understood in atmospheric fogs[10] and super fluid helium. The fundamental equations of continuity, momentum, energy and state, which lead to a "wave equation" for foggy gas must be solved in the general case numerically. For a sediment in which mass transfer is important, the physics of mass transfer in vapor saturated gasses provides the basics of a good understanding of the phenomena in sediments. Marble[11] has an easily understood description of the phenomena of mass transfer along with the coupling effects of viscosity and heat conduction.

In the immediate vicinity of a suspended fog droplets additional viscous and heat conduction losses take place over those effective in the homogeneous gas. Furthermore, a relaxation process occurs with evaporation of the water in a fog droplet as influenced by the passage of a sound wave. The normal equilibrium between the saturated vapor near the droplet and surrounding air is disturbed by the sound wave which is followed by a lag in its restoration due to heat conduction. Both of these processes lead to losses that increase gradually with frequency. At 1 kHz the measured contribution to attenuation from these sources in a realistic fog is a hundred times greater than that of a dry air and ten times that measured in humid air.

In the case of the sandstone or soil mentioned above, the throats of pores will contain water, and for low water content the bulk of the pore space will be saturated with water vapor. It is likely that mass transfer is the mechanism of attenuation in these rocks and soils. In ocean sediments, the gases which are produced by living and decaying organisms will be attached or produced at nucleation sites in the sediment material.

SUMMARY

An investigation of the effect of mass transfer of water vapor of both mostly air-and "water-saturated" porous materials. is being considered To date there exists no model which incorporates the effects of water vapor on sediment attenuation. This work leads to a model for mass transfer in sediments.

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ACOUSTICALLY ACTIVE SURFACES

ABSTRACT

Last year the ONR review team recommended that the NCPA active surfaces research group use its expertise in digitally controlling smart acoustically active surfaces to develop a waveguide with active walls capable of plane wave propagation. This guide would be used as an impedance tube for measuring the acoustical impedance of materials of interest to the Navy. As a first step in carrying out this mission, a study has been made of wave propagation in a waveguide with passive elastic walls. In this study an important discovery has been made. Calculations using a theory by Del Grosso show that it should be possible to choose the materials and dimensions of such a guide so that it will propagate a specific mode as a plane wave. An effort has been made during the past year to develop such a waveguide. Work has also continued to incorporate transducers into the tube wall and exploit active walls to generate very intense traveling waves inside a toroid.

OBJECTIVE

In keeping with the recommendations of last year's ONR review, the basic objective of the research during the past year has been to develop an impedance tube with active walls for the purpose of testing low frequency acoustic materials. The study of the basic physics involved in the propagation of sound in fluid filled waveguides has lead to the important discovery during the past year that plane wave propagation should be possible under certain conditions in waveguides with compliant walls. This discovery means that it may be possible to build an impedance tube with the desired property without resorting to using active walls.

In addition, theoretical analysis and initial experimental results of the past year's work indicated that very intense sound fields can be produced inside a toroid with active walls driven so that surface waves are generated in the toroid wall propagating with the speed of sound in the liquid.

The behavior of such a sound field and its interaction with the tube walls present interesting unanswered questions.

To answer these questions a passive waveguide has been constructed with material and dimensions carefully chosen to allow plane wave propagation with a phase velocity close to the intrinsic speed of sound in the liquid.

In addition a toroid has been constructed with active walls capable of generating very intense sound fields inside the toroid. The behavior of these sound fields and their interaction with the tube wall will be studied theoretically and compared with the experiment.

BACKGROUND

Last year, the ONR team that reviewed NCPA made the following recommendation for the active surfaces research group. "The topic of active control is relevant to many Navy applications, and we think it is in the Navy's interest to have NCPA involved. Given that NCPA has developed a working knowledge of active control, including DSP (Digital Signal Processing) and transducers, we recommend that these capabilities be applied to the development of an actively controlled impedance tube for the purpose of testing low frequency acoustic materials. The characterization of acoustic materials is a physical acoustics issue and also a critical Navy problem." In carrying out this recommendation we have conducted a study of both passive and active waveguides. The study of the passive guides was a logical beginning place in actively controlling the wall motion.

A. Passive Waveguide

A classic method of measuring the acoustic properties of a material is to use it to form the termination of a waveguide and deduce its complex specific acoustic impedance from measurements of the standing wave in the fluid. In this *impedance tube* technique, a fundamental assumption is that the wave in the fluid is planar. It can be shown that such is the case if (1) the walls of the waveguide are rigid and (2) only the fundamental propagation mode is excited. A mathematically equivalent statement is that the progressive wave mode used must have a phase velocity equal to the intrinsic sound speed in the fluid.

Although the rigid wall approximation is applicable to a solid waveguide filled with a gas, it fails for the waveguide filled with a liquid. Several authors[1,2] have studied propagation of elastic waves in liquid filled tubes, but most have treated the tube as a thin shell. On the other hand, Del Grosso[2] uses the exact lossless longitudinal and shear wave equations for tubes of arbitrary thickness and obtains the dispersion relation for axisymmetric waves. The results are so mathematically complicated that numerical techniques must be used to obtain the phase velocity of waves at a given frequency.

For example, Figure 1 shows the dispersion curves for axisymmetric modes for fresh water in a steel tube. (The abscissa in the figure is proportional to frequency; the ordinate, to phase velocity.) In general, as is the case for the rigid waveguide, there may exist several modes at a given frequency. In contrast to the rigid tube, as frequency is lowered, two modes persist down to zero frequency. In general, neither of these fundamental modes is planar nor travels at the intrinsic sound speed of the liquid. Thus, because of the finite elasticity of a solid compared to a liquid, impedance tube techniques with liquid filled waveguides are of limited utility. The goal of the work at NCPA has been to determine how liquid filled waveguides may be constructed so that they support plane waves.

During the past year an important discovery has been made using Del Grosso's theory to calculate wave propagation in PVC tubes. Quite fortuitously, it turns out that in the specific tube analyzed one mode travels with about 1/3 the speed of sound in water and the second mode that persists to zero frequency travels with little dispersion at very nearly the speed of sound in water. Further, modes with speeds close to these calculated values have been observed experimentally. What this means is that it may be possible by properly choosing the material to construct a waveguide with passive walls that will support plane wave propagation.

B. Active Waveguide

As mentioned above in the ONR review team's recommendation, the active surfaces research group at NCPA has developed compound active surfaces with both sensing and driving layers and the digital signal processing capability to drive these surfaces so as to make them

acoustically non-reflecting, non-transmitting, or both. One of our objectives in this project is to use this capability to develop a waveguide with active walls that can be driven so as to support plane wave propagation in the fluid column. During the past year in analyzing theoretically the sound wave expected to be propagated in such an active wall guide, it was observed that waves of infinite amplitude result in an infinitely long tube when the radial wall motion corresponds to a surface wave traveling with the intrinsic speed of sound in the enclosed fluid. From these calculations we have concluded that very high intensity traveling sound waves (differing from shock waves) will be generated in a toroid when the toroid circumference is large compared to its cross section diameter and its circumference is equal to a whole number of sound wavelengths in the fluid.

According to private communication with Dr. David Blackstock, this device was conceived by H. E. von Gierke in 1960. He named it an "acousticron", but we prefer "acoustitron". According to Dr. Blackstock, von Gierke constructed a devise that produced sound pressure levels of 160 dB using a small sound source. Dr. Blackstock tried unsuccessfully to construct one in the 1970's. His problem was that he was not able to eliminate the wave traveling in the reverse direction[3]. During the past year we have constructed and successfully demonstrated a square wave guide 109 cm long with 32 active wall sections driven with the needed phase control to propagate the forward wave and eliminate the backward wave. We propose during the coming year to construct acoustitrons with both water and air as the wave medium, and to study theoretically and experimentally the waves produced.

RESEARCH PROGRESS IN FY93

Progress during the past year can be divided into the following areas:

1) Transducing materials.
2) Electronic hardware for phased array control.
3) Waveguides with passive compliant walls.
4) Waveguides with active walls
   a. infinite length, lossless medium with specified: (1) wall velocity, (2) pressure and (3) driving voltage (theoretical).
   b. infinite length, lossy medium, with specified wall velocity (theoretical).
   c. finite length, lossless medium, with specified wall velocity (experimental).
5) Control of wall impedance with active elements.

The progress in these areas is discussed below.

1) Transducing materials. Dan Warren completed his Ph. D. dissertation in which he analyzed theoretically and studied experimentally transflexural transducers capable of use in low frequency active panels.

2) Hardware for phased array control. In order to drive array elements with time shifted wave forms, a single input, multi-channel output delay amplifier is needed. Not being able to find such a circuit on the commercial market, one has been constructed and tested. Its use to drive transducers in the walls of a square waveguide is discussed below.

3) Waveguides with passive compliant walls. In the past year, using the theoretical results of Del Grosso as a starting point, we have studied the propagation of low frequency modes in passive liquid filled waveguides of infinite length. In taking the zero frequency limit of Del Grosso's dispersion relation for axial symmetric modes, we have found that the intercepts of the dispersion curves with the phase velocity axis satisfies a quadratic equation. This equation, with coefficients determined by properties of the waveguide and enclosed liquid, provides a simple analytical method of determining the low frequency phase velocity limits for a given waveguide. The resulting equation shows that within a restricted range of material parameters and tube thicknesses, it is possible to construct a passive waveguide with a low frequency mode having a phase velocity equal to the intrinsic sound speed of the liquid. Thus, in principle a passive pseudo-rigid waveguide is possible.

The limiting conditions for construction of such a pseudo-rigid wall waveguide depend upon three parameters: (1) Poisson's ratio of the wall material, (2) the ratio of the intrinsic sound speeds in the solid and liquid, and (3) the ratio of the outer to inner diameters. Under certain conditions, these three parameters give rise to a limiting phase velocity equal to that of the intrinsic speed of sound in the liquid; i.e., a pseudo-plane wave mode exists. Figure 2 shows the range of values of the first two parameters for which such conditions exist. For materials with these parameters, a proper choice of tube dimensions results in a pseudo-rigid waveguide mode. For materials outside the shaded area of the figure, no tube size can produce such a mode.

To exploit these results, an effort has been made to construct a pseudo-rigid wall waveguide. As seen in Figure 2, a candidate for such a waveguide is water in PVC. In fact, common Schedule 40 PVC water pipe of 3.0 in ID and 0.25 in wall thickness has been used in the apparatus described in Figure 3, and theoretical calculations show this system to have a mode with phase velocity differing less than one percent from the intrinsic sound speed in fresh water.

Phase velocities of two low frequency modes in this waveguide have been measured using tone burst signals received by the hydrophone at different distances from the source.

Measurements of initial phase velocities of the two most prominent modes are shown in Figure 4. The experimental values differ from those predicted by Del Grosso's axisymmetric theory by more than the uncertainty in the measurements. When wall motion was examined via accelerometer measurements, it was seen that asymmetric modes were being excited, and the disagreement of the measured phase velocities with those predicted from theory are tentatively attributed to that asymmetry.

In order to excite only the desired axially symmetric pseudo-plane wave mode a transducer at one end of the waveguide must produce a particle displacement profile on the cross section of the system (liquid and wall) identical to the profile characteristic of the mode. In addition to axial symmetry requirements, our theoretical calculations show that the longitudinal particle displacement in the wall of the present experimental system is an order of magnitude greater than that in the liquid in the pseudo-plane wave mode. This means a coaxial pair of transducers will be needed, one to drive the wall and the other, the liquid. In the present system with its single piston driver and tone burst driving signal, several modes of excitation are observed. A major part of the experimental effort in the coming year will be the development of a transducer source that efficiently produces only the desired mode, and to study the performance and operation of such passive wave guides.

4) Waveguides with active walls. We have spent much effort in both the theoretical and experimental study of acoustic waveguides with active walls. Such a system, of course, is not simply a passive acoustic transmission line but is a sound source. We have solved theoretically for the progressive wave produced in a liquid or gas by the polarized progressive wave vibration of the waveguide surface for both cylindrical and square waveguides. Schematically, one could envision such an excitation being produced by the apparatus in Figure 5. Here a liquid cylinder is surrounded by a linear array of ring transducers driven at the same amplitude but progressively different phase.

4a. Theoretical calculation for an infinitely long lossless waveguide. In the steady state, the phase velocity of the wave in the liquid equals that of the surface wave in the wall. The wave amplitude in the liquid depends on the amplitude, frequency and wave number of the wall vibration and the length of the tube. But it also depends upon what property of the wall motion is being controlled. Three different cases have been considered theoretically for cylindrical modes in an infinitely long tube enclosing a lossless medium. The three controlled qualities considered are control of the wall displacement, control of the pressure at the wall, and control of the voltage applied to a wall made of a specific transducer material (piezo rubber). In the latter case, pressure release is assumed outside the tube. In each case, when the velocity of the surface

wave in the wall equals the velocity of a particular mode in the fluid, the amplitude of the wave in the fluid goes to infinity. This might be expected in an infinitely long tube since the wall motion moves with the fluid wave always adding energy to this traveling fluid wave. The calculations for the cylindrical guide are shown in Figures 6a, b, and c. The calculations were made by applying the appropriate boundary conditions to the solution of the wave equation in cylindrical coordinates. The solution assumes that the axial and time dependence of the fluid wave is the same as that of the controlled wave in the wall, i.e., $e^{i(k_d z-\omega_d t)}$.

The "ridges" in Figure 6a trace wall wave speeds and frequencies that correspond to fluid modes with rigid wall boundaries, in 6b the ridges correspond to fluid modes with pressure release boundaries, in 6c the ridge with values of $c_d/c_0 \succ 1$ corresponds to a pressure release mode, but the very narrow ridge that is traced by spikes (due to the finite grid spacing) we think corresponds to a slow velocity mode in a guide with soft walls. The soft wall condition results from driving the piezo rubber with a pressure release backing. The resulting wave is the same as the slow velocity wave discussed in the section above on passive guides.

4b. Theoretical calculations for an infinitely long lossy waveguide. When the medium in the waveguide has viscosity and thermal conductivity, the customary analysis attributes the total vibrational motion of the medium to three different modes, the acoustic mode, the vorticity mode, and the entropy mode[4]. We have applied the controlled radial velocity boundary condition to the Rayleigh solution for these three modes and calculated their amplitudes in the infinitely long tube. This time we plot the ratio of the axial and radial particle velocity to the amplitude of the wall velocity. The calculations show that the vorticity and entropy waves are negligible except in a boundary layer for all cases except where the wall wave speed is equal to the speed of sound in the fluid. Figures 7a and b show the axial and radial particle velocities in the tube as function of r. Figure 7a shows the vorticity wave cancels the acoustic wave close to the surface bringing the total axial velocity to zero at r = a (to comply with imposed boundary conditions). The effect of the vorticity wave on the axial particle velocity is seen to be confined to a region close to the surface. However, this is not the effect for the radial component. Figure 7b shows the plot of the radial velocity as a function of r for the case of zero viscosity and thermal conductivity. Figure 7c shows the same plot assuming the viscosity and thermal conductivity of water. The surprising thing about 7c is that the viscosity causes the radial velocity to drop to zero outside of the boundary layer when $c_d/c_0 = 1$. Figure 8a and b show the radial components of the acoustic and vorticity waves. The significant thing shown by these curves is that at $c_d/c_0 = 1$ the wall vibration causes a radial vorticity wave in the boundary later but no radial acoustic wave. Figure 9 shows a plot of the radial velocity at r = .9a for the case where $c_d/c_0 = 1$ as a function of the normalized vorticity skin depth. Evidently the transfer of

radial motion into axial motion at this critical wall velocity is dependent upon the viscosity of the liquid. This phenomena is not yet understood but it may have importance in allowing such surface waves to control flow separation in turbulent flows over surfaces. Surface vibration has been observed to affect the flow separation from the surface in experiments performed at NCPA[5].

4c. Experimental study of finite waveguides with active walls. The initial experimental efforts to construct an active wall tube is diagrammed in Figures 10a, b, and c. It consists of a square aluminum tube 2.8 cm on an inside edge and 109 cm long. On the inside of each wall are 32 flexural piezoelectric transducing discs 2.78 cm in diameter, a total of 128 elements in all. These elements consist of a thin disk of piezoelectric ceramic bonded to a thin brass disk. Each disc is mounted over a cylindrical cavity so that the brass surface is flush with the waveguide walls (see Figure 10b). The transducers are glued in place with flexible silicone glue so that the disc can vibrate in its unclamped mode, and so that there is a minimum of coupling of the vibration to the tube wall. The centers of the discs are 3.02 cm apart.

To each end of the tube is attached an extension containing a pyrex wool cone to eliminate reflection and thereby prevent standing waves. The circuit used to drive the transducer consists of an 8-bit analog-to-digital converter, thirty-two 8-bit digital-to-analog converters, and a high speed memory as seen in Figure 10c.

The output of the input converter is stored in memory in a large array. The memory is located on a digital signal processing card located inside a PC. With each successive input, the digital reading is "pushed through the buffer". The data from 32 different equally spaced positions in the buffer are pulled out and loaded into 32 registers. The "distance" between the buffer positions corresponds to the time delay from one channel to the next, the latter being controlled by input from a PC. The output is then fed through a 32-channel unity gain amplifier to drive the capacitive load presented by the flexural elements.

Monitoring of the acoustic signal levels inside the tube is done with two Knowles microphones located at the ends of the tube. They are glued to the wall of the tube for convenience. Figure 11 shows the measured ratio of sound at the "rear" of the tube to that at the "front". Also shown is the "theoretical" curve expected for this ratio when one adds the output of each section with the proper delay. In the forward direction the programmed delay cancels the travel time delay to allow the sound from all of the elements to add. In the backward direction, at certain frequencies the sound from the different elements adds to zero. This occurs when 32 times the phase difference between the sound from adjacent elements is some whole multiple of 2π radians.

5) Control of wall impedance with active elements. During the past year in initial efforts to actively control the wall impedance of a fluid filled tube, transflexural disks were glued to the outside of a PVC pipe containing water. The initial results indicate that such a configuration could be used to drive the tube walls and generate sound waves in the fluid column. It is obvious that the most difficult job in this case is going to be controlling the backing impedance against which the active layer will be "pushing". In work reported to previous committees, we have demonstrated that it is possible to build an active surface composed of a sensory layer and two driving layers and drive this surface so as to eliminate both a reflected wave and a transmitted wave. This work was reported in a final report on ONR contract N00014-90-5-4068.

This same configuration could just as easily be programmed to eliminate the transmitted wave and to totally reflect the incident wave. As long as the transmitted wave is eliminated such a surface operates independent of the backing impedance. Rather than trying to use the tube wall itself as the backing impedance for the active layer, (this would greatly complicate the global control) we propose to build a composite wall composed of two active layers separated by an inertia layer. The two active layers will then be driven so as to make both the surface in contact with the liquid and the surface in contact with the wall stationary. The composite wall and its motion is diagrammed in Figure 12. Most of the work during the coming year will involve developing panels with this composite structure and the needed control circuits. It may be possible to drive these individual cells with inexpensive, self contained analog circuits.

RESEARCH PROGRESS IN FY93

During the past year two important discoveries have been made. The first is that a passive waveguide can have "pseudo" rigid walls for frequencies all the way to zero for properly chosen tube wall properties and dimensions. An effort will be made to exploit this discovery in the construction of a passive wall impedance tube during the coming year.

The second discovery is that driving an active wall of a tube so as to support a surface wave in the wall traveling with the intrinsic sound speed in the fluid column can produce strange effects for infinitely long tubes. By approximating the infinite length using a toroid, it may be possible to experimentally investigate these effects. Such a device has been named an acoustitron.

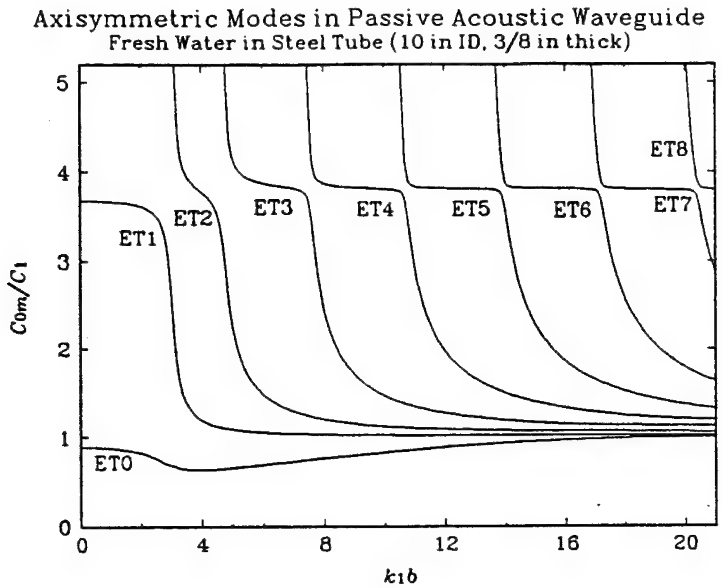


Figure 1. Dispersion curves for axisymmetric modes in an elastic waveguide.

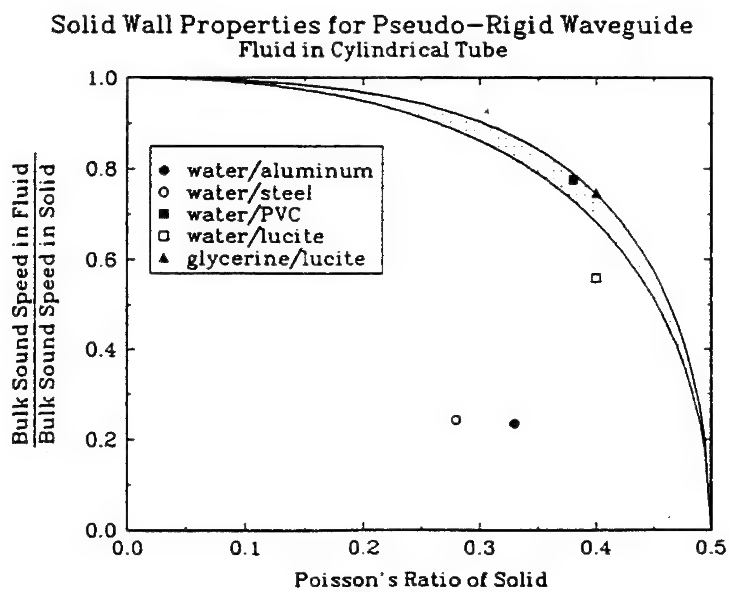


Figure 2. Range of material parameters allowing a pseudo-rigid passive cylindrical waveguide. If a fluid/solid combination has properties that place it within the shaded region, a proper choice of tube diameter and thickness can be made to produce a waveguide supporting a fundamental mode that, in the limit of zero frequency, has a phase velocity equal to that of sound in the bulk liquid.

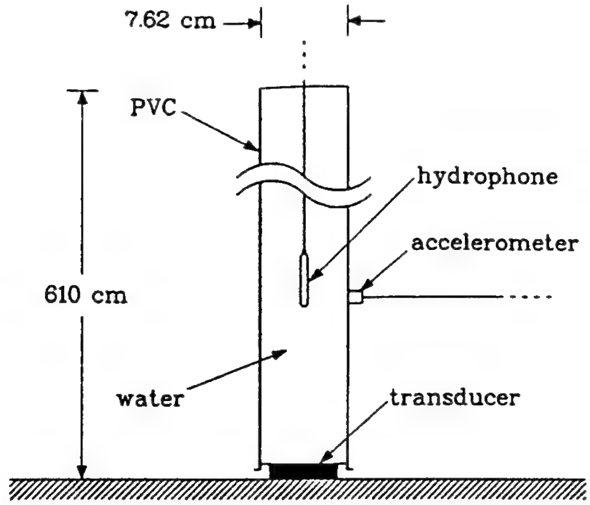


Figure 3. Experimental apparatus for measurement of modal phase velocities and wall vibrations in a passive water filled PVC waveguide.

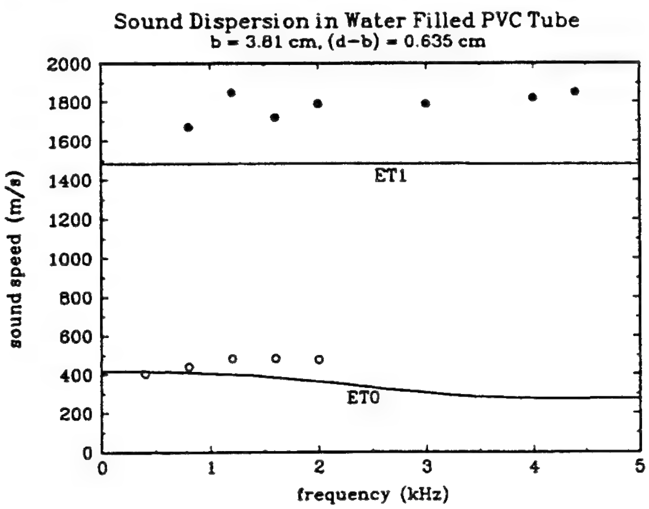


Figure 4. Experimental determination of modal phase velocity in a passive PVC waveguide.

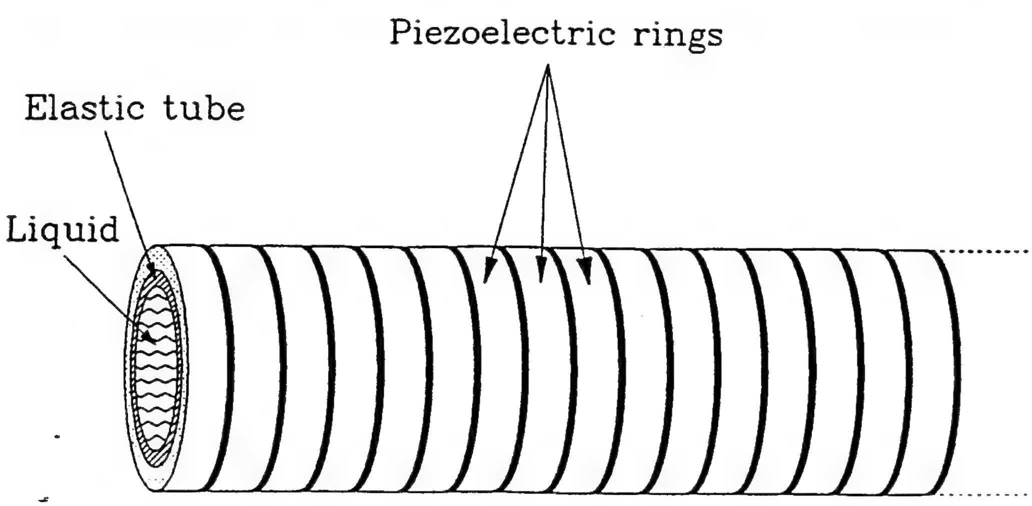


Figure 5. Concept of active waveguide using independently phased piezoelectric ring transducers surrounding liquid cylinder and perhaps, elastic tube.

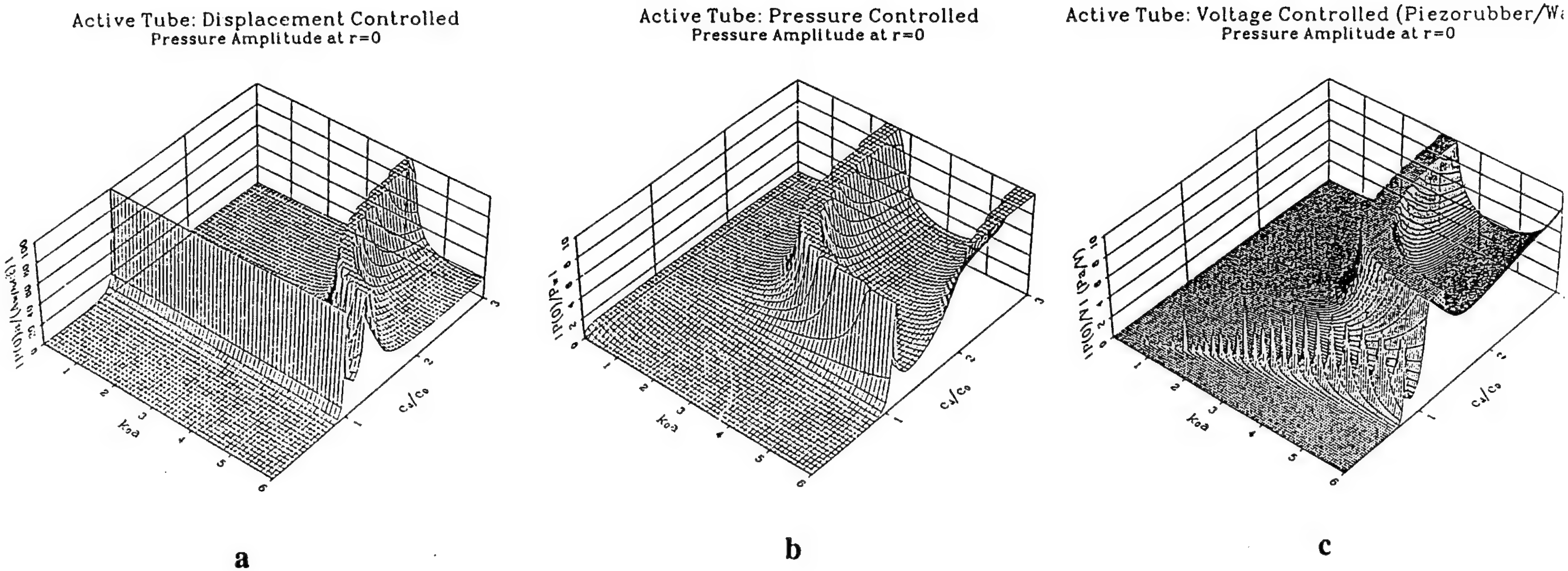
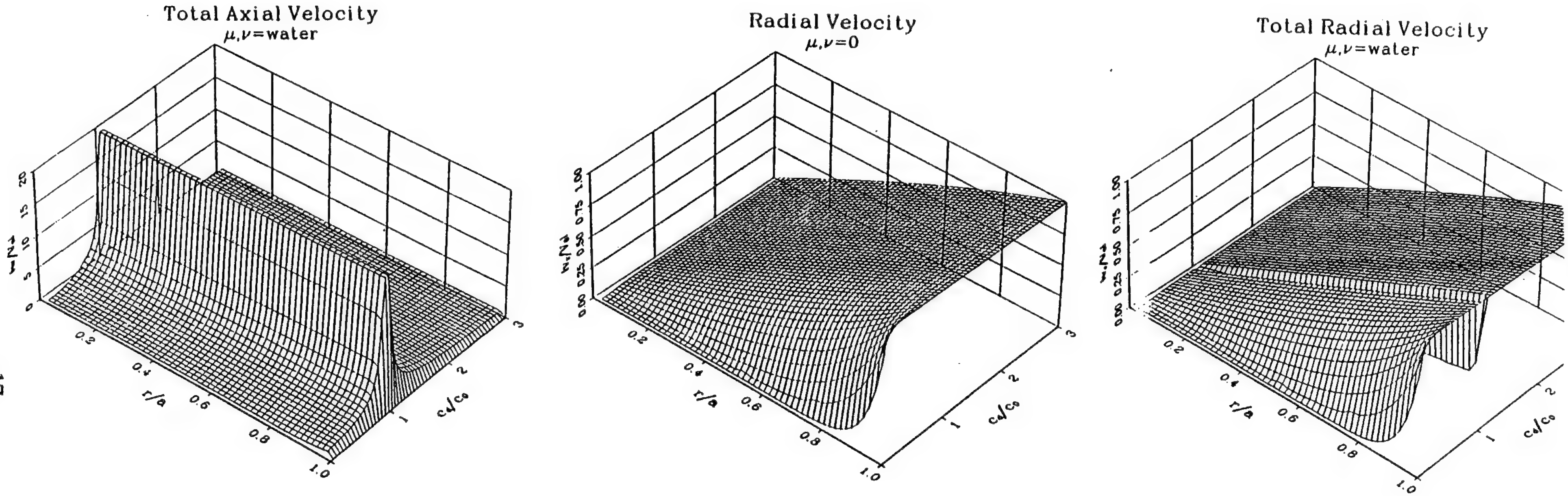
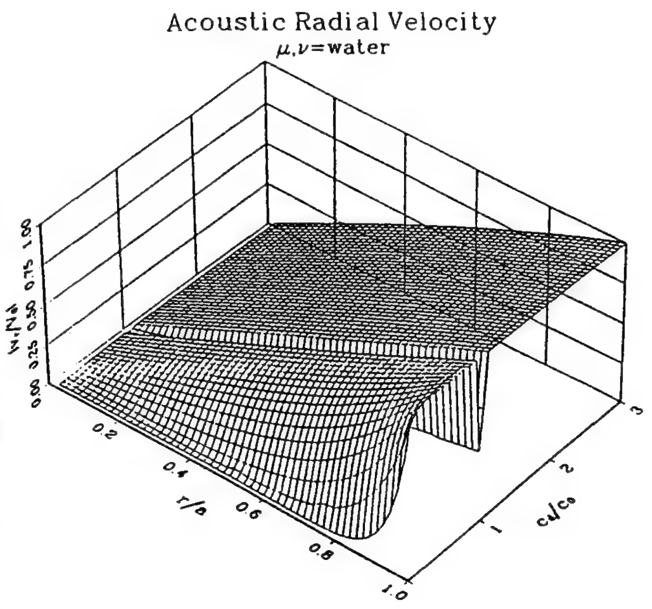


Figure 6. Amplitudes of acoustic waves on the axis of infinitely long waveguides with active walls. In 6a the active wall is driven with a radial velocity given by $-iA_w\omega_d e^{i(k_d z-\omega_d t)}$ where A_w is the amplitude, ω_d the angular frequencies, and k_d the wave number of the surface wave in the wall. The ordinate is the dimensionless quantity sound pressure times tube radius divided by displacement amplitude times the bulk modulus of the liquid. In 6b the wall is driven so that the sound pressure at the wall is given by $P(0)e^{i(k_d z-\omega_d t)}$, and in 6c, a wall made of segments of piezo rubber is driven with a voltage given by $Ve^{i(k_d z-\omega_d t)}$.

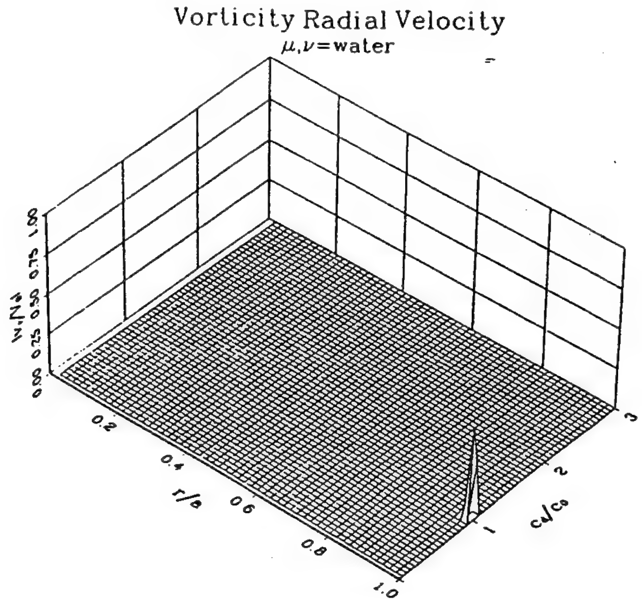


a b c

Figure 7. Sound particle velocities with $k_d a = 1$ in an infinite wave guide with walls driven with a radial velocity given by $V_0 e^{i(k_d z - \omega_d t)}$. w is the magnitude of the axial particle velocity, V_r is the radial particle velocity, $C_d = \omega_d / k_d$ is the wave speed in the wall, ω_d and k_d the frequency and wave number of the surface wave in the wall and C_0 is the intrinsic sound speed in the fluid. 7a is the total axial particle velocity in water, 7b is the total radial velocity without viscosity or thermal conductivity and 7c is the total radial velocity with viscosity and thermal conductivity.



a



b

Figure 8. The radial particle velocity in water. (a) the part due to the acoustic wave and (b) the part due to the vorticity wave. In water the entropy wave is very small. Curves 8a and 8b add together to give curve 7c.

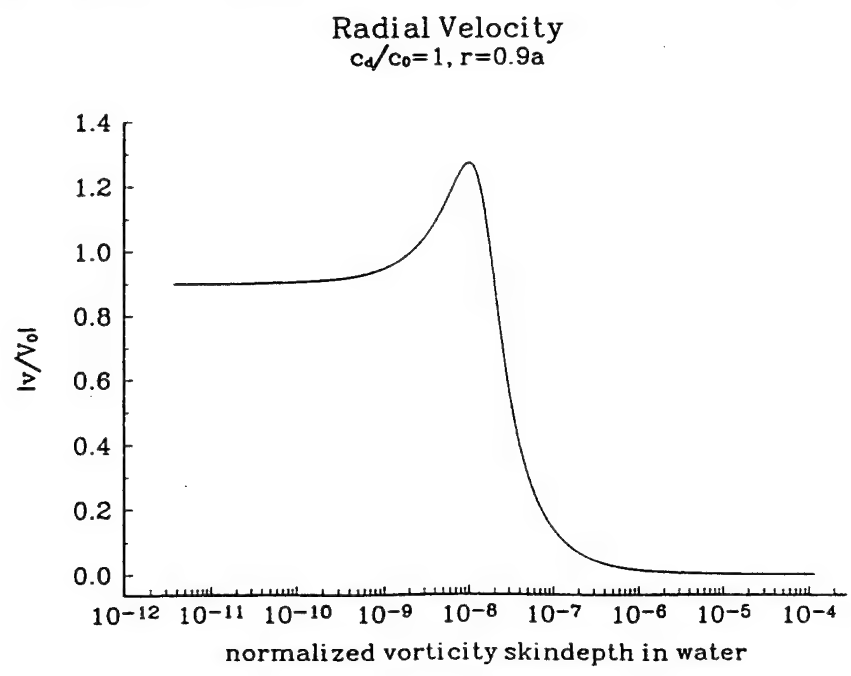


Figure 9. Figures 7b and 7c show that viscosity has a striking effect in reducing the radial component of the particle velocity in the active wall waveguides. This figure plots the effect as a function of viscous skin depth and shows that the effect occurs when the normalized skin depth is greater than about 10^{-8}. The skin depth is defined as the square root of two times the viscosity divided by the angular frequency times the density. The normalized skin depth is this quantity divided by the tube radius.

The Phased Array Tube

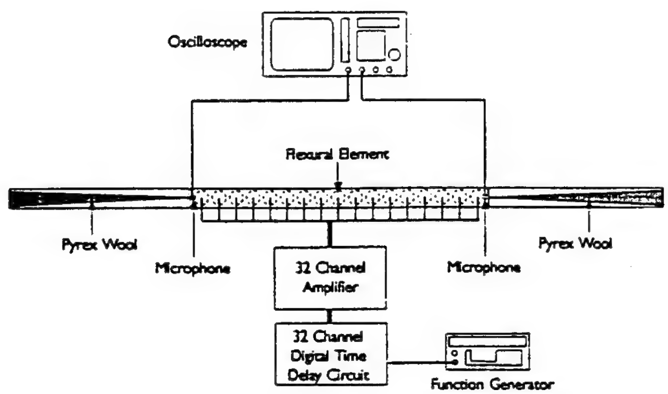


Figure 10(a). Diagram of the square phased array waveguide and its control circuit.

Placement of Piezoceramic Transducers

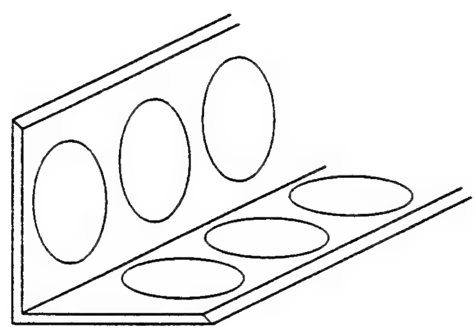


Figure 10(b). Cutaway of two walls of the phased array waveguide showing circular transflexural discs mounted in the wall.

32 Channel Digital Time Delay Circuit

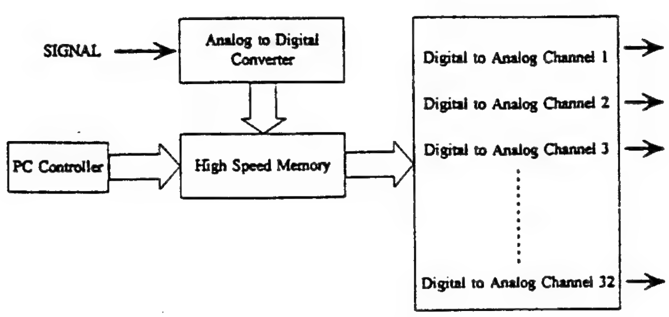


Figure 10(c). Block diagram of the phased array waveguide control circuit.

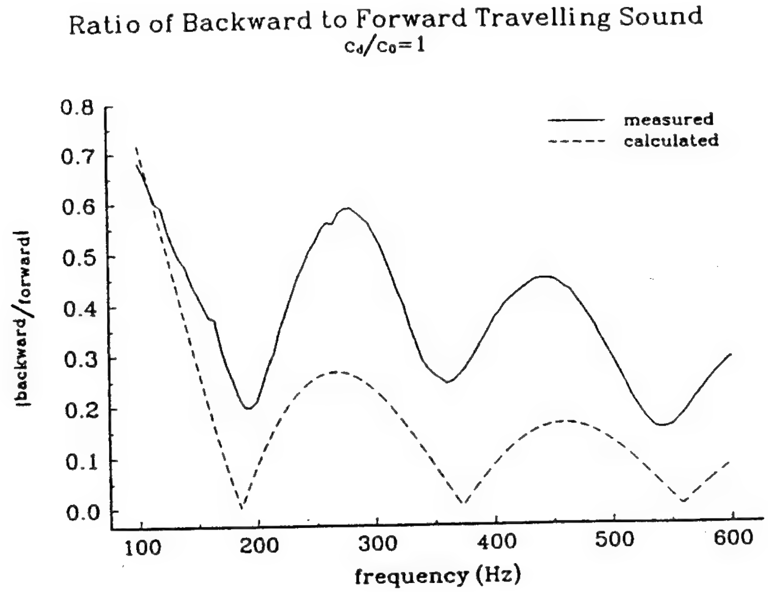


Figure 11. Ratio of the response at the microphone at the backward and forward ends of the phased array waveguide.

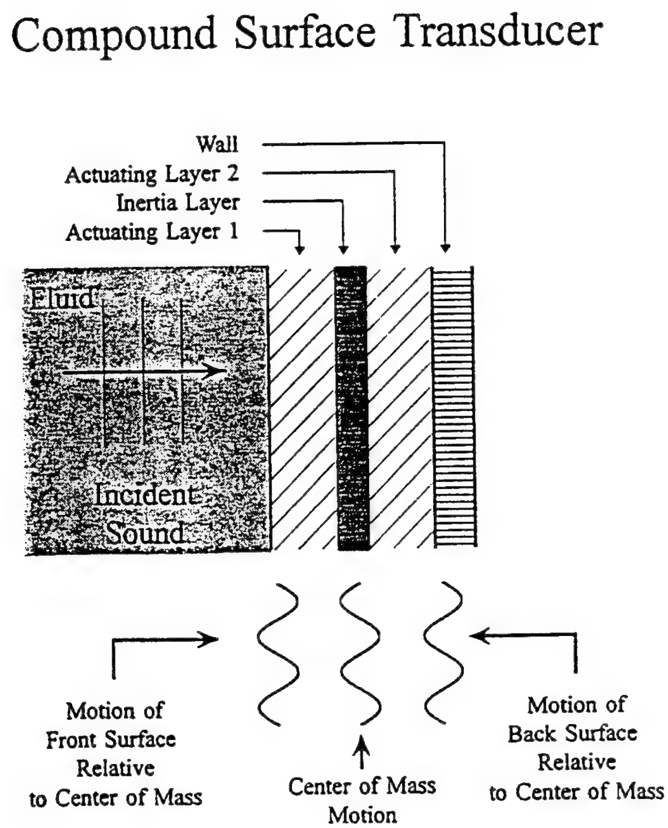


Figure 12. Diagram of the motion of layers in a composite active surface composed of two actuating layers separated by an inertia layer. The motion of the center of mass produced by the incident sound plus the driven motion of the two actuators combined to make the front and back surfaces stationary.

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GRADUATE FELLOWSHIPS

The National Center for Physical Acoustics is an integral part of the University of Mississippi, which has a strong reputation for its graduate programs in physics, mathematics and engineering. Recruiting qualified US students into a Ph.D. program with research emphasis in acoustics is a high priority for NCPA. The NCPA fellowship program was developed with the hope that outstanding undergraduates would be identified and attracted to the University for specialized training in acoustics at NCPA. By offering these young scientists hands-on experience in this discipline, they would upon graduation be capable of filling positions in Navy Laboratories and/or facilities that conduct work relevant to acoustics.

In FY 91, NCPA received funds from the Office of Naval Research to administer a graduate fellowship program in acoustics. A limited number of applicants were awarded fellowships because of the high criteria we set for admission to this program and due to the

limited number of available awards. The criteria for admission were revised further in 1993. We believe that this program has given more visibility to acoustics as a specialization in physics, and that visibility is in the best interests of the Navy. Six NCPA Fellows were supported by these funds in the past year. These were:

Adam Calabrese. Mr. Calabrese is continuing his work in transient microcavitation under the direction of Professor Crum at the University of Washington. He remains a student in the University of Mississippi graduate program. Mr. Calabrese's tenure as an NCPA Fellow was completed in May 1993. He now expects to graduate in early 1994..

Paul Elmore. Mr. Elmore's Ph.D. research involves studies of nonlinearities in crystal structures. His research is directed by Dr. Mack Breazeale. Mr. Elmore successfully completed the comprehensive examinations in the fall of 1992 and expects to graduate in December, 1994.

Jay Lightfoot. As a freshman graduate student, Mr. Lightfoot performed extraordinarily well in freshman graduate courses in physics. His research in the area of thermoacoustics is directed by Dr. Bass. Mr. Lightfoot successfully completed the comprehensive exams in the fall of 1993.

Keith Olree. Mr. Olree has also proven to be an outstanding graduate student. He is doing research in active noise control under the direction of Dr. Shields. He also successfully completed the comprehensive exams in the fall of 1993.

Daniel Warren. Dr. Warren successfully completed the requirements for the Ph.D. in the summer of 1993. His research involved measurements and modeling of a flexural transducer embedded in an elastic frame. Dr. Warren accepted a position at Peavey Electronics in Meridian, MS upon graduation.

The graduate fellowship program has proven to be one effective tool in recruiting outstanding students and provides the student an opportunity to perform innovative research. Last year we proposed to replace Mr. Calabrese and add one additional student for a total of six. During the spring of 1993, we received only one application for an NCPA Fellowship from an applicant with a truly outstanding undergraduate record. That student declined our offer of a fellowship.

In part, the scarcity of qualified applicants was due to an increase in minimum qualification (see attached brochure). It is our plan to reserve these fellowships for truly outstanding students only.

NEW INITIATIVES IN THE PHYSICS OF ACOUSTICS

INTRODUCTION

NCPA grew out of a Physical Acoustics Research Group at the University of Mississippi and it was initially envisioned that NCPA would address critical research topics in Physical Acoustics. Toward this end, the Navy Review Committee recommended that $100,000 be set aside in 1993 for the hiring of new faculty in physical acoustics in order to enhance the appropriate technical base.

Following receipt of guidance from the Navy Review Committee, possible areas of research interest were discussed internally and with Dr. Hargrove in ONR. Based on these discussions, we chose to limit our search to candidates in non-linear systems or solid state/materials sciences. A number of candidates in these areas were interviewed (a total of eight). Again, following discussions with Dr. Hargrove and Dr. Schlesinger at ONR, we chose to hire Dr. Bruce Denardo from the Naval Postgraduate School. Dr. Denardo began his duties in August, 1993.

Dr. Denardo was hired as a tenure track Assistant Professor in the Department of Physics and Astronomy. The New Initiative funds set aside were used to purchase equipment, provide for travel, etc. necessary for Dr. Denardo to begin a research program at the University of Mississippi. These new initiative funds provided support through the summer of 1994 at which time, Dr. Denardo will request support through conventional channels. We consider the acquisition of Dr. Denardo a major achievement. There is every indication that he will be able to make major contributions to non-linear acoustics and interact well with existing research groups.

Research in Nonlinear Waves

This document is a summary of current and prospective forefront research. The areas are (1) solitons, (2) absorption of sound by anisotropic noise, (3) wave turbulence, and (4) breakdown of adiabatic invariance. Most of this work involves efforts to uncover and understand fundamentally new and general behavior of nonlinear waves. It is accomplished by performing experimental, analytical, and numerical investigations of particular systems (e.g., surface gravity waves, sound in gases and liquids, and vibratory mechanical lattices), and by focusing on interesting aspects that are suspected to occur in a wide variety of systems. In many cases, this generality can be established to a significant extent.

In addition to the work in the fundamental topics below, work is beginning in several areas of research that have immediate impact on applications. There are two aspects of

thermoacoustics that are being considered. First, large-scale drivers are necessary for practical applications of thermoacoustic refrigeration. Such possibilities are being surveyed, including parametric excitation which is a novel means that has not yet been achieved in acoustics. Second, the nonlinear nature of the flow in the heat-reservoir stack is not understood. A perturbative analytical approach is being considered to describe this behavior. Research in wave beams is being considered, in particular, the possibility of employing interleaved nonlinear acoustic beams to achieve transverse localization.

Solitons

Nonlinearity can give rise to behavior that is fundamentally different from linear behavior. This is dramatically exemplified by solitons, which are exponentially self-localized waves on constant shape in dispersive systems. In such a wave there is a stable balance between nonlinearity, which tends to cause the wave to shock, and dispersion, which tends to cause the wave to spread (because components of different wavelengths travel at different speeds). Solitons were first observed as surface waves in a canal in 1834,[1] and are planned to be employed this decade as optical signals in transoceanic fiber lines.[2] Solitons may also play a role in energy and information transfer in some biological systems .[3]

Based on the observation of a localized standing surface wave *breather* in a long uniform channel of deep liquid,[4] a *cutoff kink* soliton in the shallow liquid case was predicted and consequently observed.[5] In the breather state, the liquid is motionless except in a relatively small region where it sloshes transverse to the channel. In the kink state, the liquid sloshes at constant amplitude transverse to the channel in two extended regions with a 180° phase difference. This kink is the localized transition that connects the motion in the two regions. The observations showed that this state can exist at amplitudes beyond which the perturbation theory is valid, indicating that the state is a more general phenomenon than the theory predicts.

Experiments with a mechanical lattice have yielded analogous breather and kink solitons and, more importantly, fundamentally new types of localized states.[6] These are *domain walls*, which are localized transition regions that connect two standing wave regions of different wave number, and *noncutoff kinks*, which connect two noncutoff standing wave regions of the same wave number with a difference in spatial phase. No previously known modulational equation describes these new states. An understanding of the states may thus lead to new solitons which may offer advantages over those planned for use in fiber optic communications. Recently, the analytical description of domain walls and noncutoff kinks in continua have been successful.[7]

A possible continuum analog of the lattice noncutoff kink is currently being investigated. Steady-state longitudinal standing waves can be maintained on the surface of a deep liquid in

vertically-oscillate annular channel. If the drive frequency is slowly and monotonically changed, and the drive amplitude is fixed at a sufficiently large value, the transition to the next mode is accompanied by the spontaneous formation of a localized kink structure characterized by larger amplitude and shorter wavelength compared to the extended mode region. This kink can appear at any location of the annulus, and dies out as the transition is completed. This *kink-assisted mode hopping* , which is currently being investigated experimentally, may have applications to the problem of unwanted mode hopping in diode lasers.[8] It was recently discovered that it is possible to obtain permanent kinks at sufficiently high drive levels. These are violent structures that continually exhibit breaking of the surface. This remarkable observation of localized turbulence in a translationally invariant (uniform) system may aid in the understanding of the phenomenon of intermittency in turbulence.

This soliton work has been funded by several grants from the Naval Postgraduate School Direct-Funded Research Program. The work on the mode hopping experiment is currently being done in collaboration with Charles McClelland, a previous student who is now an instructor at the US Naval Academy. Three areas in which preliminary work has been done, and future work is planned, are *bulk solitons, soliton shedding,* and *higher-dimensional solitons.*

Regarding solitons in bulk liquids or solids, there is currently only one such observation, which is of a Korteweg-de Vries soliton in a gas-liquid mixture.[9] Observations in conventional media are important because they could not only lead to applications, but also because fundamental questions arise regarding the thermodynamics of localized waves, which are far-off-equilibrium states. With geophysicist Prof. Gerard Schuster at the University of Utah, a collaboration has begun to consider the possibility of employing solitons to transmit acoustic energy into bore holes in the earth, and detecting the resultant signals on the surface in order to tomographically image the surrounding region.

In soliton shedding, one end of a wave guide is driven at a frequency outside the linear propagation band. Above a drive amplitude threshold, propagating breather solitons are spontaneously shed at a definite rate, even though the drive amplitude and frequency are constant. This effect was first observed in a large surface wave tank.[10] It has been shown both experimentally and numerically that soliton shedding can occur in lattices as well, indicating the generality of the phenomenon. Furthermore, it has been shown that the quasi-periodicity associated with high-amplitude breathers is a result of soliton shedding. There is currently no explanation of the effect.

Regarding higher-dimensional solitons, to our knowledge there has yet to be an observation of a soliton in more than one spatial dimension. It is believed that two dimensional steady state breathers may exist, and have in mind several systems as candidates. The current knowledge of the two-dimensional self-focusing instability in actual systems is that it cannot be

stabilized (leading, for example, to dielectric breakdown in optics). It is suspected that drive and dissipation in our systems will lead to stable two-dimensional structures.

Absorption of Sound by Anisotropic Noise

Another area of current work involves finite-amplitude acoustic noise. For isotropic noise in two or three dimensions, small fluctuations from an equilibrium spectrum are predicted and have been observed to relax exponentially.[11-14] In contrast, small fluctuations from a one-dimensional spectrum are predicted to relax as a *gaussian* ,[15] which are independently predicted based on a different analytical approach. The lack of exponential decay is due to the inability of one-dimensional acoustic noise to equilibrate as a result of non-linear wave interactions. The inability exists because all of the waves resonantly interact in this case, leading to a far-off-equilibrium steady state.[16] The gaussian attenuation, which has not yet been observed, is important as a possible general characteristic of far-off-equilibrium systems. One interesting and potentially useful aspect of this attenuation is that it breaks translational invariance. Specifically, by taking measurements at several distances from the source of a signal, one can calculate the location of the source. (This cannot be done if the attenuation is exponential.)

An experimental investigation to observe the effect in air is currently being headed. The construction and testing of the apparatus, which is a high intensity traveling wave tube of length 21 m and inner diameter 5 cm, has recently been completed. The apparatus consists of seven 10-foot sections smoothly joined by collars and flanges, and is mounted on a wall in the basement hallway of the Physics Department of the Naval Postgraduate School. Attached to one end of the tube is a housing that contains two compression drivers connected to the tube by a "Y" adapter. One driver will generate the noise, and the other will generate the signal. An anechoic end termination spans the length of the last section.

This project is being done in collaboration with Anthony Atchley and Andres Larraza. The project is currently being funded by the Naval Postgraduate School Direct-Funded Research Program.

Because a variety of interesting research in nonlinear acoustics can be accomplished with the apparatus described above, plans are being made to build a new apparatus here at NCPA. One future experiment is to drive the tube slightly above the first cutoff frequency such that the noise is not purely one-dimensional, in order to probe the transition from gaussian to exponential attenuation. Another future experiment is to search for new collective modes by modulating the noise (refer to Wave Turbulence below). Another future experiment, as recently suggested by Prof. Oleg Rudenko of Moscow State University, is to investigate the possible suppression of noise by a pure tone.

Wave Turbulence

In any wave system that is driven sufficiently far from equilibrium, there is predicted to occur a cascading of energy from lower frequencies (where the energy is assumed to be input) to higher frequencies (where the energy is ultimately dissipated as heat). The result is a steady state power law spectrum.[17] This redistribution of energy among random waves is referred to as *wave turbulence.*

Wave turbulent spectra have been observed in several systems, including gravity waves in a stormy sea.[18] However, no controlled experiments have been performed in order to establish the existence of wave turbulence. Furthermore, the wave turbulence is predicted to have new collective modes which have not yet been observed. These modes involve the propagation of compressions and rarefactions of the turbulent wave energy. One mode occurs at wave lengths large compared to the mean free path of the collisions of the turbulent waves, and is analogous to "second sound" in superfluid helium.[19] The other mode is the collisionless limit of the first. In this case the wavelength is small compared to the mean free path, and the mode is analogous to "zero sound".[20,21] The existence of these new modes is important in ocean wave physics because they should provide an efficient means of redistribution of energy .[20]

To test the theory, an experiment is being conducted in a wave tank that is 20 m long, 1.2 m wide, and 1 m deep. A broad band background of gravity waves is generated by wind from a bank of fans, and a modulated noise pulse is generated by a paddle. According to the theory, the modulation will propagate nondispersively at a speed determined solely by the background wave energy and effective density (analogous to pressure and density of a gas of particles). Time of flight measurements will determine whether the propagation is nondispersive, while spectral energy measurements will provide the required values to test agreement with the theory.

Dr. Denardo is collaborating with Robert Keolian and Andres Larraza on this project. They are being funded by the Office of Naval Research through an Accelerated Research Initiative for Nonlinear Ocean Waves.

One problem has arisen in the wind-wave tank. The observed power law of the spectrum is not that predicted by the wave turbulence theory. The new modes can still exist, however, and recent observations indicate that zero sound may be present. In order to test the theory of the wave turbulent spectrum, conducting an experiment in a large tank with a plunger that mechanically generates surface waves in a low frequency band is planned. The nature of the cascading of energy to higher frequencies will then be observed. This energy input source is simpler and more controllable than wind, and should thus allow an indisputable conclusion regarding the existence of wave turbulence.

Breakdown of Adiabatic Invariance

Adiabatic invariance, in which certain quantities that characterize a system remain unchanged as external parameters are slowly varied, plays a fundamental role in much of physics. For example, the entropy of a closed thermodynamic system remains constant as the system is subjected to slow mechanical changes. The underlying quantum statistical description of this process is that the occupation numbers corresponding to the energy eigenstates are constant during such changes. In fact, the "old" quantum theory was based upon the axiom of quantifying the adiabatic invariants of the motion. Many practical techniques owe both their utility and limitations to adiabatic invariance; for example, geometrical or "ray" theory in underwater acoustics, and the bending of microwave radiation in wave guides.

For external changes that are infinitely smooth but not infinitely slow, there is predicted to be a very weak breakdown of adiabatic invariance: the change in the adiabatic invariant of the initially excited state, and the excitation of other states, are *exponentially suppressed.* Specifically, if ε is a dimensionless positive number that tends to zero in the limit of infinitely slow external changes, then the changes in the adiabatic invariants of the system ate proportional to $\exp(-1/\varepsilon)$.[22] For changes that are not infinitely smooth, the suppression is algebraic rather than exponential: the changes are proportional to ε^n, where n is the order of the order of the derivative that is discontinuous.[23] Remarkably, these very mathematical statements do not appear to have been tested experimentally. Because no external changes in real systems can be infinitely smooth, the exponential suppression is not expected to be observed. The breakdown may thus serve as a probe of the smoothness of the external changes.

The supervision of a master's thesis student, who performed numerical simulations in the breakdown on adiabatic invariance in several single-oscillator systems, has recently been completed. The important conclusions were that (a) the exponential suppression was not observed, despite careful attention to the numerical methods, and (b) the dependence of change in adiabatic invariant upon the initial phase persists to the limit of infinitely slow alterations, which is a surprising result whose prediction is not, to our knowledge, in the scientific literature. Regarding (a), it may be that very sophisticated methods and a very fast computer are required to observe the exponential suppression.

In the future, plans are being made to perform one or more acoustics experiments in the breakdown of adiabatic invariance. In one, a longitudinal wave in a tube will encounter a constriction whose characteristic length is large compared to the wavelength. The reflected amplitude and the change in the transmitted amplitude, which represent a breakdown in adiabatic invariance, will be carefully measured as a function of the relative length of the constriction. In

another experiment, a nonlongitudinal mode of a rectangular wave guide in which one section has a 90^{o} twist, will be excited. The extent to which the energy in the mode is altered by reflection into the mode will be measured, and by scattering and transmission into the mode with the other polarization. This more complicated situation is interesting because there is now a competition among ways in which the adiabatic invariance can break down.

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OCEAN ACOUSTICS

Bubble-Related Noise from Breaking Waves

Introduction

Over the years considerable attention has been devoted to the understanding of ambient sound in the ocean. Recent conferences devoted to the understanding of the source mechanisms for ambient noise production at the sea surface have lent further support to the contributions of gas bubbles as the principal source of this noise[1,2]. However, a detailed description of the specific role of bubbles has not yet been given. Bubbles created by breaking waves at sea are recognized to be the major factor in the Knudsen[3] wind noise generation, radar backscattering, and sea surface acoustic reverberation. Breaking waves give rise to bubble plumes which penetrate a distance of several meters under the ocean surface and persist for as long as several minutes. These clouds play an important role in the reverberation and backscattering of underwater sound of immediate and high sea states. Recent laboratory studies of gently spilling breaking waves concluded that the source of noise is newly created bubbles oscillating at their linear resonance frequency[4]. Laboratory measurements of noise generated by stronger breaking

waves were also reported[5] where the absolute noise level measurements were not obtained because of the reverberation of the tank/flumes. Measurements of noise generation by breaking waves at sea were recently reported for which the contributions from distance sources were eliminated by using a vertical array of hydrophones instead of omnidirectional hydrophones[6]. In these reports the source level measured directly above the array shows a correlation between wind speed and noise intensity. Recent open-ocean measurements of the noise generated by breaking waves[7-8] and the free field and laboratory measurements of noise generated by transient water jets[9-10] in fresh and salt water suggest that the frequency of the noise could range as low as several tens of Hz. Since breaking waves produce sound at low frequencies, the collective oscillations was proposed as the source of low-frequency ambient noise[11].

There exists ample evidence to suggest that sound scattering from the sea surface possesses a characteristic which is different from that expected by Bragg scattering from gravity waves[12]. It is our contention that breaking waves result in bubble clouds or plumes that can efficiently scatter sound. Indeed, recently published works[13] indicate a significant role for bubble plumes in surface backscatter. In spite of vast responsibility, too little is known about the dynamics of breaking waves and the associated noise generation to quantify directly the relationship between the two phenomena. The principal focus of this project is to investigate the hydrodynamics and acoustic characteristics of bubble clouds/plumes generated by laboratory breaking waves.

Research Progress in FY93

A plunger-type wavemaker was used to generate various breaker types and intensities. The detailed description of the experimental set-up, data collection, and data analysis along with results and discussion of the measurements of the absolute sound pressure levels, and hydrodynamic characteristics of bubble clouds obtained from various 2-D breaker intensities are reported in an article to be submitted to JASA[14]. In these measurements, we were able to carefully reproduce the conditions for each breaking wave event and also average over at least 100 separate events. A brief discussion of the results is given below.

Figures 1-3 show power density plots for weak spilling, moderate spilling and plunging breakers, respectively. The power densities shown in these figures were averaged over 100 samples. The weak breaker has a prominent peak at around 2 kHz. The spectral slope of the noise from the weak breaker is roughly 6 dB/octave from 2 kHz to 20 kHz and follows f^{-2}. Increasing breaker severity entrains more air and produces larger bubbles. The power density of the moderate breaker shown in Fig. 2 clearly indicates a shift to lower frequencies. This figure has a broad-band spectral peak with a maximum at around 600 Hz corresponding to a bubble size of 1.1 cm in diameter. The spectral slope of this figure is roughly 5 dB/octave from 500 Hz to

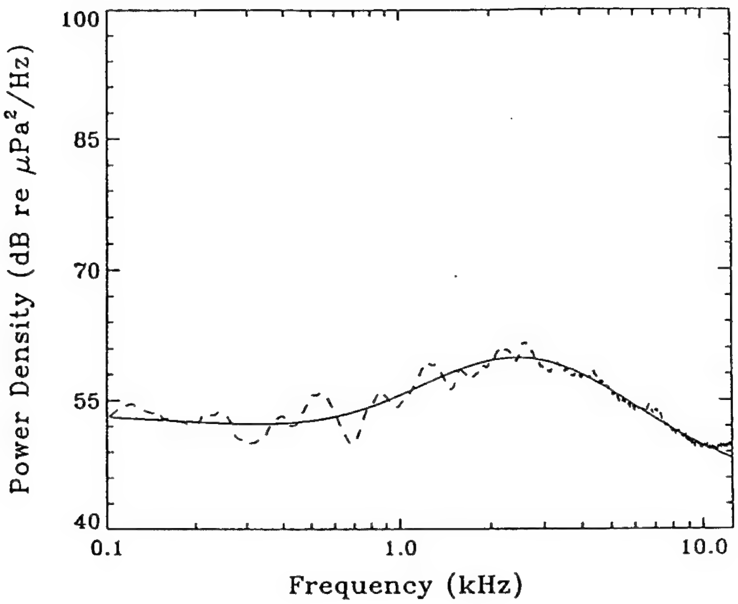

Figure 1

Power density averaged over 100 acoustic signals of the weak spilling breakers with a peak at around 2 kHz. The solid line is the best curve fit to the data.

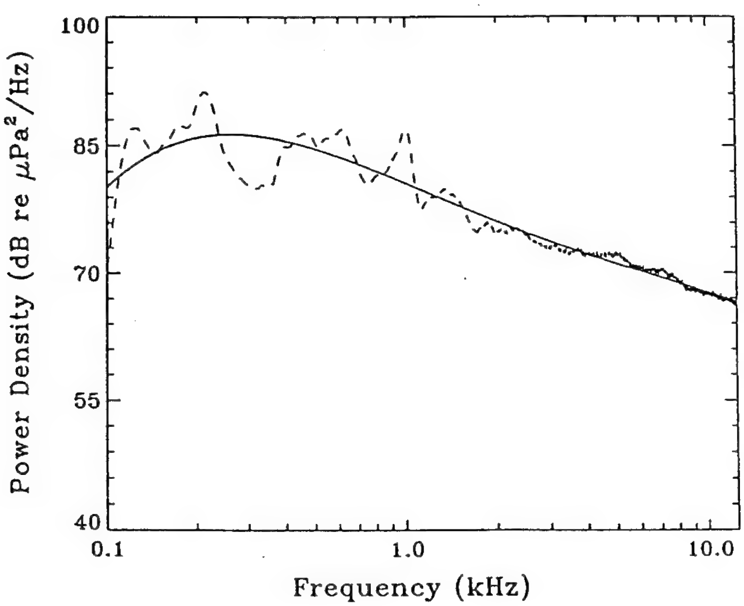

Figure 2

Power density averaged over 100 acoustic signals of the moderate spilling breakers with a peak at around 600 Hz. The solid line is the best curve fit to the data. Note the existence of significant spectral components for frequencies as low as 100 Hz. The peaks near 550 Hz and 950 Hz are most likely due to modes in the tank; the peak at 200 Hz is significantly below the cut-off frequency of the tank.

12.5 kHz. This slope is close to that obtained for wind dependent ambient noise in the ocean which follows $f^{-1.5}$ behavior. Finally, the shift in the spectral peak to about 200 Hz is evident in the power density shown in Fig. 3 for plunging breaker. The significant broad-band, low-frequency noise generation below 200 Hz demonstrates that collective oscillations of bubble clouds are a possible mechanism.

Fig. 4 shows the histogram of the bubble size distributions of the weak spilling breaker. Note that a few individual bubbles in the range 1.1 - 2.2 mm are created, thus producing sizes capable of generating the observed spectra in the 1.5 - 2.0 kHz ranges, as shown in Figure 1. The generation of larger bubbles by spilling breakers is evident from the bubble size histogram shown in Fig. 5 which demonstrates the existence of bubbles in the 5.0 mm range, and corresponds to an acoustic frequency of 650 Hz. Of course, these bubble sizes just described correspond to the large-end of the spectrum. These larger bubbles are also much more efficient in radiating energy. On the lower-end of the spectrum, Figs. 2 and 3 show an increase in spectral density of about 20-25 dB from the weak breaker shown in Fig. 1. The collective oscillations of bubble clouds are believed to be responsible in this region. An important corollary of the ambient noise issue is the inverse problem. Figure 6 is a plot of the average acoustic energy versus the total energy in the gravity wave group prior to breaking. The correlation between radiated acoustic energy and wave energy prior to breaking may be useful in monitoring wave energy. One could use this noise to learn important oceanographic facts that are otherwise inaccessible.

Preliminary results of the scattering properties of various bubble clouds generated from breaking waves were investigated. The use of a parametric source in the anechoic tank environment proved to be not a reliable source. Instead, we used a conventional Navy F42A source with a parabolic reflector which served to concentrate the energy in a narrow beam direction (~30°). Figure 7a and b shows echoes of a 10 kHz, 10 cycle tone burst in the presence of waves with and without breakers, respectively. The first group of waves is the incident waves measured at 1 m from the bubble cloud and the second group is the backscattering signal from bubble clouds and/or surface roughness. This technique will help us to isolate the acoustic scattering strength of the bubble clouds from the effects of the surface roughness.

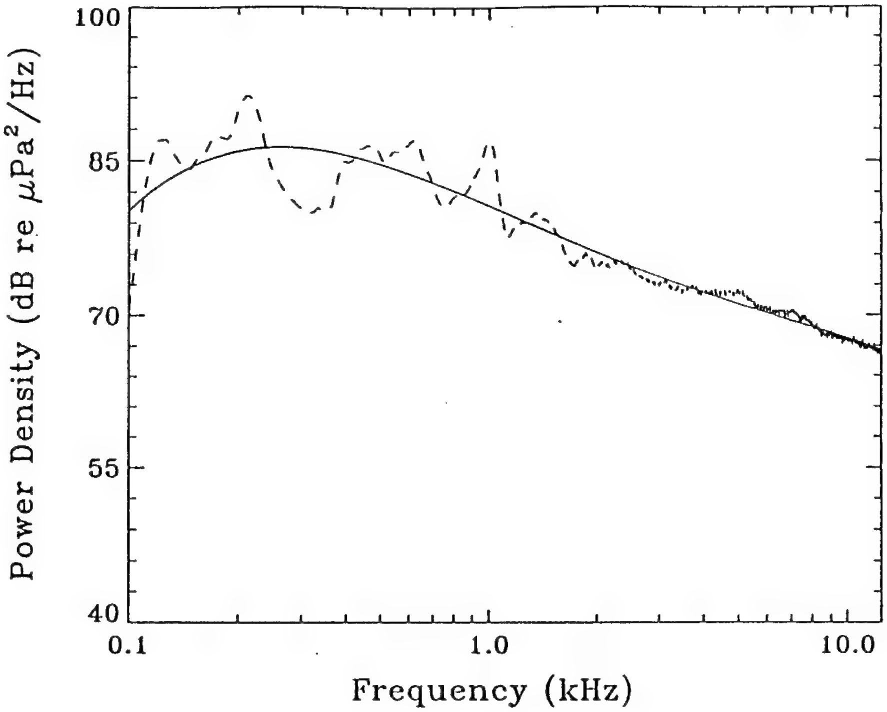

Figure 3

Power density averaged over 100 acoustic signals of the weak plunging breakers with a peak at around 200 Hz. The solid line is the best curve fit to the data. Note the shift from low intensities and high frequencies in Fig. 1 to the relatively high-intensity and low frequencies for this case. The peaks near 500 Hz and 950 Hz are below the cut-off frequency of the tank and may represent collective oscillations of bubble clouds formed by the breaker.

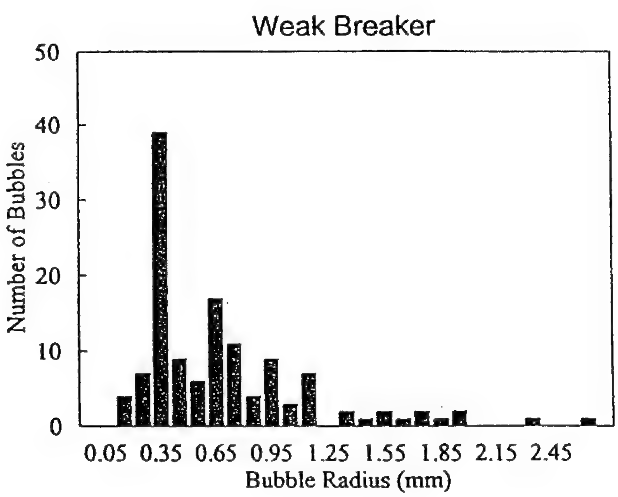

Figure 4

Histogram of bubble production by weak spilling breaker.

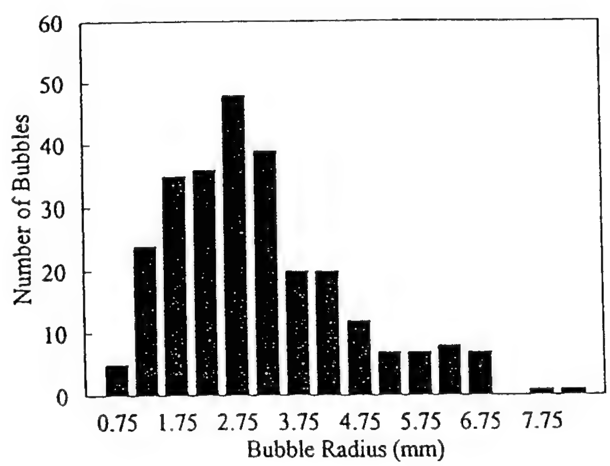

Figure 5

Histogram of bubble production by moderate spilling breaker. Note the existence of relatively large bubbles. For the case of salt water, one would expect significantly smaller bubbles.

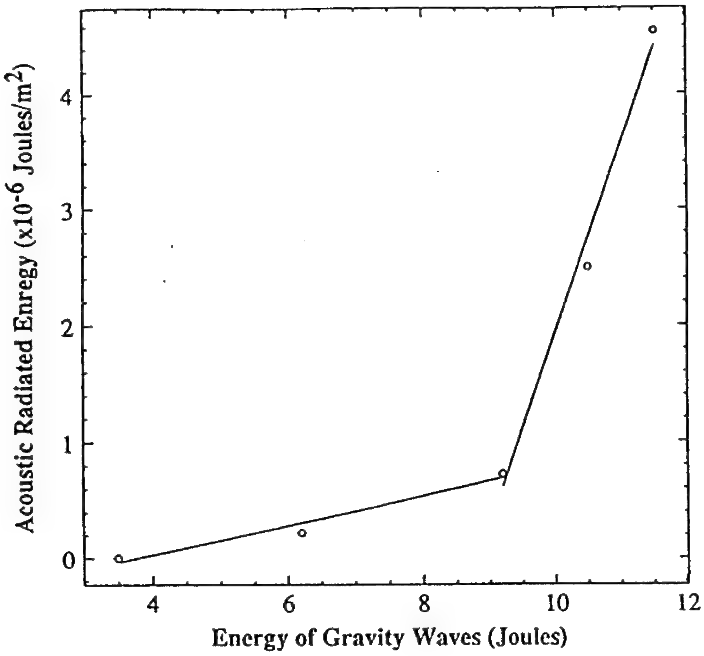

Figure 6

Correlation between the acoustic radiated energy due to breaking with the total energy of the waves prior to breaking. The drastic change in slope probably is associated with the transition from spilling to plunging breaker behavior.

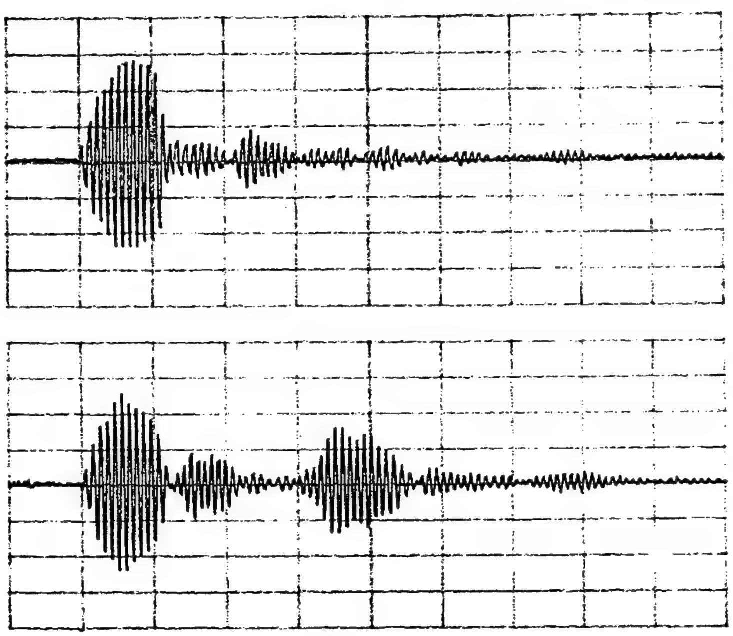

Figure 7

Typical scattering results obtained with a conventional source with a reflector operating at 10 kHz frequency. The 10 echo returns serve to illustrate the evolution of the echo level at the presence of the gravity waves without breaker (a) and with breaker (b).

Bubble-Related Noise in Turbulent Flows; Hydrodynamics Activation of Bubbles

Introduction

It is well known that turbulence is a weak radiator of sound. The radiation properties of turbulent flow in water have been shown to be greatly modified by the presence of a small distribution of air bubbles in the turbulence[16] . This process may be relevant to the underwater sound generation at low and high frequencies. Sound production mechanisms in a turbulent flow containing bubbles can include break-up and coalescence of bubbles, bubble enhancement of low-frequency turbulence noise, and excitations of bubbles. In the ocean, the air entrainment process by breaking waves generally occurs in the first half of the breaker active life. After air entrainment has ceased, the forward region of the mixed air-water flow degenerates into a chaotic highly turbulent motion. The foe of this turbulent region runs forward on the undisturbed water surface like a bore with a celerity significantly higher than the celerity of the breaking crests. The highly chaotic motion of turbulent flow field may distort and deform bubbles contained in the field. We seek to characterize the sound production of adult bubbles encountering the fully developed turbulent flow field.

Research Progress in FY93

In order to examine the sound production mechanisms in a turbulent flow containing bubbles, we have developed a system that enables us to introduce gas bubbles into a turbulent region. A simple experiment was set-up that injects bubbles into an axisymmetric, turbulent flow. The detailed experimental set-up is reported in an article about to be submitted to JASA[17]. A brief discussion of the results are given below.

Using high-speed cinematography we were able to correlate the bubble dynamics in the turbulent field and acoustic emissions from it. We have shown that an adult bubble encountering a turbulent jet can re-radiate sound through nonlinear coupling between surface mode and volume pulsations. This mechanism is illustrated in Fig. 8 where a bubble of 1.1 mm in radius was allowed to encounter a turbulent jet produced by a nozzle of 3.10 mm in diameter with an exit velocity of 2.2 m/sec. Fig. 8a shows the pinch-off acoustic pressure radiation followed by a sound pressure of the surface mode coupling with volume modes. The power spectra of these signals are shown in Fig. 8b. The coupling has exactly the same frequency as the infant bubble oscillation. Figure 9 is an example of where multiple coupling may occur between the surface mode and the volume mode. This figure has the same nozzle parameters as Fig. 8. Finally, Figure 10 is a typical acoustic signal of an adult bubble encountering a turbulent jet with an exit

velocity of 2.5 m/sec produced by a nozzle of 3.10 mm. In this case the adult bubble (1.1 mm) breaks into two smaller bubbles with frequencies of 3.6 kHz and 6.5 kHz. These figures along with high-speed cinematography (not shown here) serve to illustrate that the turbulent jet can indeed lead to the bubble fission and fusion.

The 3-D stereoscopic particle tracking velocimetry (SPTV) was implemented for measuring the flow parameters and resulting bubble response in a turbulent jet. The detailed experimental set-up and data processing technique used to characterize the turbulent two phase flow are reported in a separate article[18]. The quantitative instantaneous velocities of the flow along with all the Reynolds stress components of the flow containing bubbles were measured. Figure 11 shows the experimental measurements of the mean horizontal velocity profile of the jet at a distance of $\frac{x}{D} \sim 10$ from the nozzle for $Re_D = 6800$ (where D is the nozzle diameter). Based on Prandtl's mixing-length theory, a simple theoretical calculation can be derived for circular, submerged jet, at a distance x from it. The width of the jet was shown to be proportional to x and the center-line velocity $u \sim \frac{1}{x}$. This gives a constant virtual kinematic viscosity which leads to the velocity distribution. The experimental and theoretical mean velocities are compared in Figure 11. The turbulent Reynolds number, Re_l, based on the root-mean square turbulent velocity and the Taylor lateral microscale, is given by $Re_l = \sqrt{\frac{\sqrt{\overline{u'^2}}\,l}{\nu}}$; where ν is the viscosity. Figure 12 shows the non-dimensional fluctuating velocities in horizontal and lateral directions. The region of high Reynolds shear stresses are at a distance of about one diameter from the center line. This is the region where an adult bubble was re-excited and nonlinear coupling between the surface mode and volume mode has occurred. The turbulent Reynolds number, Re_l, estimated to be approximately 23 in this region. This leads to the estimation of Kolomogrov microscale, defined as $\eta = (15)^{-\frac{1}{4}} Re_\ell^{-\frac{1}{2}}$, of about 50 μm. The smaller eddies in the region of high Reynolds shear stress are believed to be the cause of surface mode oscillations.

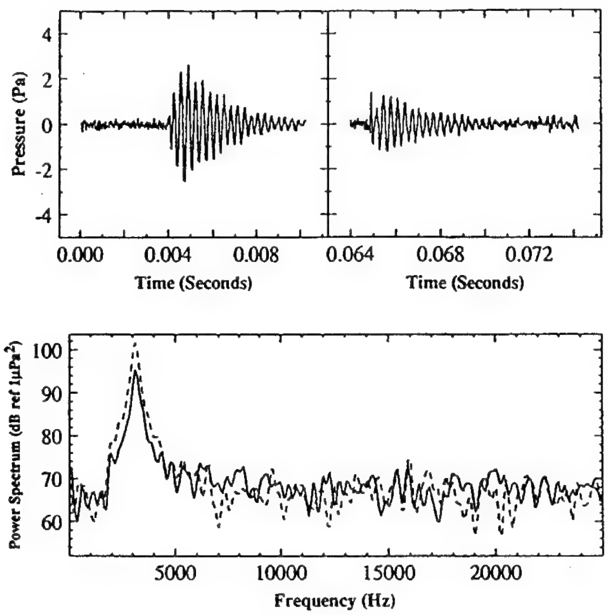

Figure 8

The pressure-time traces of a bubble of 1.1 mm in radius entering a turbulent jet with an exit velocity of 2.2 m/sec: (a) the pinch-off acoustic pressure followed by the acoustic pressure when the bubble encounters a turbulent jet., and (b) the corresponding power spectra.

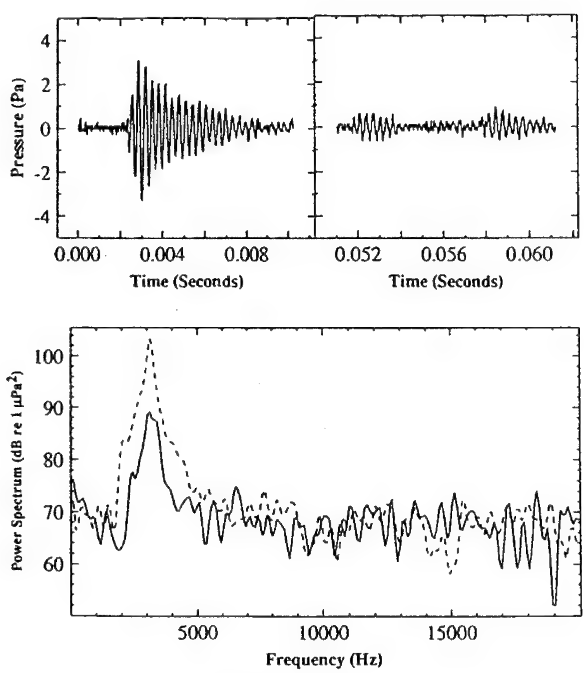

Figure 9

The same as Fig. 7, expect in this case multiple exchange of energy has occurred between the jet and the bubble.l

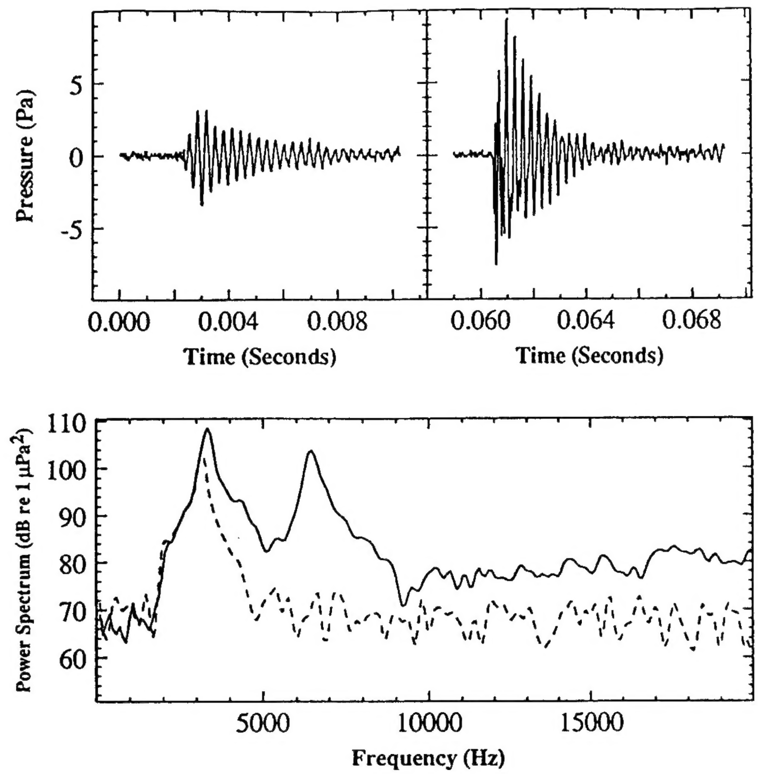

Figure 10

The same as Fig. 7, except the jet velocity has changed to 2.5 m/sec and the bubble has broken into two smaller bubbles.

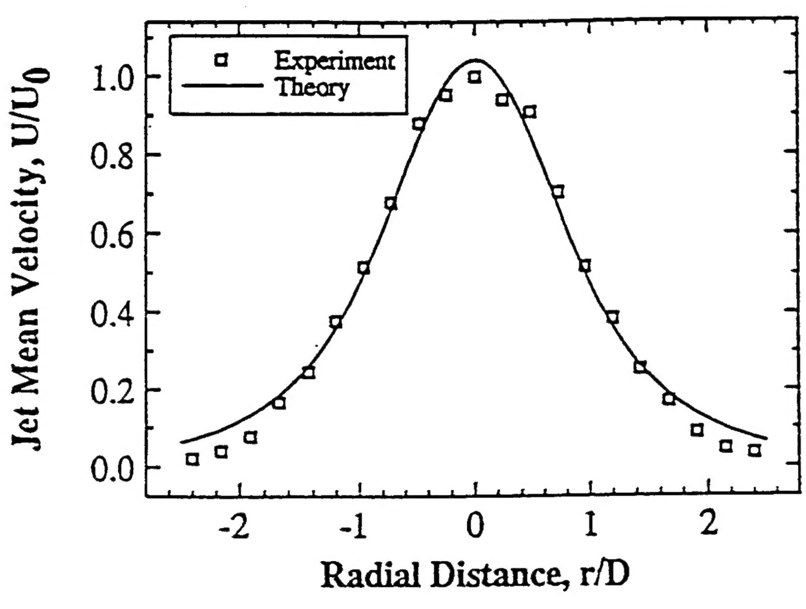

Figure 11

The experimental and theor3etical horizontal mean velocity distribution of the turbulent jet.

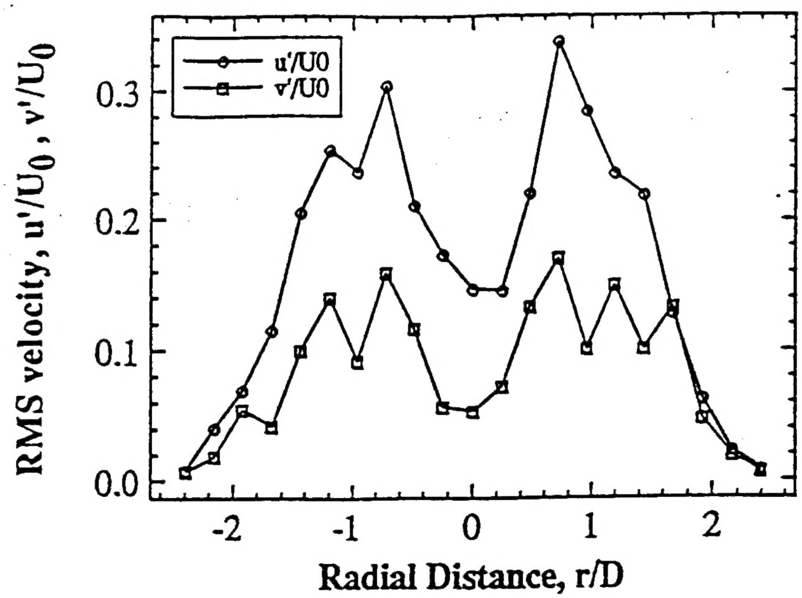

Figure 12

The axial and radial turbulent intensities. Note the nonlinear coupling between surface mode and volume mode occurs at high turbulent intensity region.

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16. Crighton, D.G. and Ffows-Williams, J.E., 1969, "Sound generation by turbulent two phase flow," J. of Fluid Mech., 36(3), pp. 585-603.

17. Kolaini, A.R., "Nonlinear coupling between surface and volume modes of an adult bubble injected into a fully developed turbulent jet," to be submitted to J. Acoust. Soc. Am.

18. Kolaini, A.R., Sinha, S.K. and Rajendran, V.P., "Bubble interaction with a fully developed turbulent flow," presented at the 20th Symposium on Naval Hydrodynamics, Santa Barbara, CA, August 1994

Publications and Presentations for FY93

A: Published papers in Referred Journals and Edited Conference Proceedings:

1. A.R. Kolaini, R.A. Roy, L.A. Crum, and Y. Mao, "Low-frequency underwater sound generation by impacting cylindrical water jets," J. Acoust. Soc. Am.,94(5), 3178-3192, 1993

2. A.R. Kolaini, A.R.. Roy, and L.A. Crum, "The production of high-frequency ambient noise by capillary waves," in Natural Physical Sources of Underwater Sound, edited by B. Kerman (Kluwer, Dordrecht, The Netherlands), 1993.

3. A.R. Kolaini, LA. Crum, and R.A. Roy, "Bubble production by capillary-gravity waves," J. Acoust. Soc. Am., April 1994.

4. V.P. Rajendran, A.R. Kolaini, and S.K. Sinha, "Characterization of an axisymmetric turbulent jet using 3-D particle tracking velocimetry," ASME, FEDSM, 155, Turbulent Flows, pp. 7-11, 1993.

5. A.R. Kolaini, "Acoustical measurements of laboratory breaking waves," Proceedings of the Third ISOPE Conference, Singapore, 1993.

6. A.R. Kolaini and M.P. Tulin, "Laboratory measurements of breaking inception and post-breaking dynamics of steep short crested waves," Proceedings of the Third ISOPE Conference, Singapore, 1993.

7. A.R. Kolaini, R.A. Roy, and D. Gardner, "Low-frequency acoustic emissions in fresh and salt water," J. Acoust. Soc. Am, in press.

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9. Y. Yuo, M.P. Tulin, and A.R. Kolaini, "Theoretical and experimental studies of three-dimensional wavemaking in narrow tasks, including nonlinear phenomena near resonance," J. Fluid Mech., in press.

B: Papers Read Before Professional Organizations:

1. A.R. Kolaini, K. Markowicz, and V.R. Rajendran, "Acoustic characterization of a bubble injected into a fully developed turbulent flow field," presented at the 125th meeting of the Acoustical Society of America, Ottawa, Canada, May 1993.

2. A. R. Kolaini, R.A. Roy, and D. Gardner, "Low-frequency acoustic emissions in fresh and salt water," presented at the 126th meeting of the Acoustical Society of America, Denver, Colorado, October 1993.

3. C.M. Hobbs and A.R. Kolaini, "Sound propagation through a bubble screen," presented at the 126th meeting of the Acoustical Society of America, Denver, Colorado, October 1993.

4. A.R. Kolaini, "Acoustical measurements of laboratory breaking waves," presented at the Third ISOPE Conference, Singapore, 1993.

5. A.R. Kolaini, M.P. Tulin, "Laboratory measurements of breaking inception and post-breaking dynamics of steep short crested waves," presented at the Third ISOPE Conference, Singapore, 1993.

6. V.P. Rajendran, A.R. Kolaini, and S.K. Sinha, "Characterization of an axisymonetric turbulent jet using 3-D particle tracking velocimetry," presented at ASME, FEDSM meeting, Washington, D.C., 1993.